Title: Reevaluating tissue analysis as a management tool for lettuce and cauliflower

Project leader: T.K. Hartz
Department of Plant Sciences
University of California
Davis, CA 95694
(530) 752-1738
(530) 752-9659 fax
hartz@vegmail.ucdavis.edu

Cooperators: Richard Smith
UC Cooperative Extension
1432 Abbott St.
Salinas, CA 93901
(831) 759-7357
(831) 758-3018
rifsmith@ucdavis.edu

Emmy Williams
Laboratory manager
Betteravia Farms
1385 Sinton Rd.
Santa Maria, CA 93454
(805) 925-7309

Executive summary:

A survey of commercial lettuce and cauliflower fields in the Salinas and Santa Maria production regions was conducted in 2004-2005 to refine the use of soil and plant tissue testing as nutrient management tools. More than 100 fields were surveyed, with roughly equal numbers of head lettuce, romaine lettuce and cauliflower fields sampled. The specific objectives were to:

1) develop broadly applicable tissue macro- and micronutrient sufficiency ranges for lettuce and cauliflower.
2) quantify the sources of variability in tissue sampling and handling to standardize practices and improve interpretation of results.
3) document the relationship between soil nutrient availability and tissue nutrient levels

In each field samples of soil and plant tissue were collected at three growth stages (early vegetative growth, midseason, and preharvest), and the status of both macro- and micronutrients was determine using established laboratory techniques. Cooperating growers provided information on fertilizer rate and commercial yield and quality for each field. Whole leaf nutrient concentrations were evaluated using the Diagnosis and Recommendation Integrated System (DRIS) approach to develop a set of nutrient sufficiency ranges for each crop and growth stage. DRIS analysis involves a mathematical comparison of leaf nutrient concentrations, and nutrient ratios, between high-yield and low-yield fields. Leaf sufficiency ranges were calculated for N, P, K, Ca,

Mg, S, Zn, Fe, Mn, Cu, and B. Additionally, leaf Na, Cl and Mo concentrations were determined, and deficiency or toxicity effects evaluated. Midrib sufficiency ranges for NO_3-N, PO_4-P and K were also calculated using data from high-yield fields found to be 'nutritionally balanced', based on DRIS analysis. Head and romaine lettuce had very similar leaf nutrient concentrations, and were combined for the DRIS analysis.

In comparison to existing recommendations from commonly used reference sources, the DRIS-derived leaf macronutrient sufficiency ranges were generally higher for N and lower for K. The only serious discrepancy between the DRIS midrib sufficiency ranges and existing references was for PO_4-P, with the DRIS values being significantly lower. The DRIS leaf micronutrient ranges were in general agreement with existing references with the exception of Ca, which we found to be in lower concentrations in both crops than the existing references suggest is desirable.

Cu was the nutrient most frequently present in concentrations below the DRIS sufficiency range, with nearly half of low-yield fields of both crops having low leaf Cu. Low leaf Cu was most common in fields with DTPA-extractable soil Cu < 2 PPM. Low leaf Mo ($\leq$ 0.2 PPM) was also common with lettuce. Additional research to determine whether soil Cu or Mo supply actually limits commercial yield should be pursued. A negative linear correlation was found between yield and leaf concentration of Na (both crops) or Cl (cauliflower only), emphasizing the importance of irrigation water quality and adequate soil leaching in minimizing the detrimental effects of these elements on crop productivity.

Leaf and midrib nutrient concentrations were similar across a range of varieties, confirming that the nutrient sufficiency ranges should be readily applicable across varieties. Neither time of day of sampling, nor post-sampling handling practices significantly affected midrib nutrient concentrations. However, midrib NO_3-N was highly variable over time, sometimes changing as much as 50% over the course of just several days. This variability was in large part due to the effects of field environment. There was a strong negative, linear correlation between midrib NO_3-N and reference evapotranspiration (ET_o) in the two days prior to sampling; warm, high sunlight conditions apparently hastened the conversion of NO_3-N to organic N compounds in the leaf. These environmental effects confounded the relationship between midrib NO_3-N and concurrently measured soil NO_3-N, casting serious doubt on the value of midrib testing as a fertilizer management tool.

Comparison of grower fertilization practices with soil and leaf nutrient levels provided some useful insights into how fertilizer management can be improved. Seasonal N fertilization varied among fields from 27 - 392 lb/acre for lettuce, and from 116 - 459 lb/acre for cauliflower. However, there was no correlation between fertilizer rate and either yield or leaf N concentration, suggesting that over-fertilization was common. Similarly, there was no relationship between P fertilization rate and soil test P level. Indeed, many of the cooperating growers simply fertilized on a 'recipe' basis, with all fields of a given crop receiving the same fertilizer, regardless of soil characteristics or soil test levels. While the net effect of this approach to fertilization was wasteful application of N and P, there was evidence that 'recipe' fertilization resulted in inadequate K fertilization in a number of fields.

Introduction:

Plant tissue analysis is an established practice in the commercial vegetable industry. Both petiole analysis for unassimilated nutrients (NO_3-N, PO_4-P, and K) and whole leaf analysis for total nutrient concentration are common. Tissue testing has been widely advocated as a fertilizer 'best management practice'. However, in recent years a number of studies have cast doubt about the validity of commonly suggested nutrient 'sufficiency' levels, or even whether tissue testing is a useful management practice. Collectively, these studies found a) poor correlation between tissue nutrient concentration and concurrently measured soil nutrient availability, b) a high degree of variability in tissue nutrient concentration in adequately fertilized crops from different fields, and c) unrealistically high nutrient 'sufficiency' standards for several crops. These findings call into question the practical value of tissue analysis and interpretation as currently performed. This project proposed a comprehensive review of tissue analysis for two important cool-season vegetables (lettuce and cauliflower) to revise currently suggested sufficiency levels, quantify the effects of potentially confounding environmental factors, and reevaluate sampling and handling techniques.

Objectives:

1) Develop broadly applicable tissue macro- and micronutrient sufficiency ranges for lettuce and cauliflower.
2) Quantify the sources of variability in tissue sampling and handling to standardize practices and improve interpretation of results.
3) Document the relationship between soil nutrient availability and tissue nutrient levels.

Methods:

A survey of 112 commercial fields was conducted from spring, 2004, through fall, 2005, in the Salinas and Santa Maria production areas. The fields were divided among head lettuce (35), romaine lettuce (43), and cauliflower (34). Fields were chosen to cover the production season from early spring through fall, with fields scattered from low ET_o environment near the coast to higher ET_o environments farther inland. Sampling was conducted on more than 20 ranches, representing more than 10 grower/shipper operations.

Fields were sampled at three growth stages: 1) early vegetative growth; 2) midseason (early heading stage for lettuce, early button formation for cauliflower); and 3) preharvest (within a week of harvest). At the early sampling a composite soil sample (0-12 inch depth) and at least 20 whole plants (lettuce) or 20 whole leaves (cauliflower) were collected. At the midseason and preharvest stages soil (0-12 inch depth), whole leaf and midrib samples were collected; the youngest wrapper leaf (and midrib thereof) was sampled for lettuce, and whole leaves and midribs 3-4 nodes down from the growing point were sampled for cauliflower. All plant samples were rinsed with dilute detergent solution and oven-dried within several hours of collection. Table 1 describes the analyses performed. All analyses were conducted by the UC Davis Analytical Laboratory; the analytical procedures used are listed on their website (http://danranlab.ucdavis.edu/).

Participating growers provided the following information: variety, planting and harvesting dates, seasonal fertilizer rates, and the commercial yield of the field. Growers also rated crop quality (good / fair / poor) and noted any field in which the yield did not reflect the productivity of the crop (poor market conditions, serious disease or insect damage, etc.) so those fields could be excluded from the data set.

The Diagnosis and Recommendation Integrated System (DRIS, Walworth and Sumner, 1987) is a mathematical framework that compares nutrient concentration differences between low- and high-yielding crops. In the DRIS approach, differences in tissue nutrient ratios between low- and high-yield fields are used to evaluate the degree to which various nutrients may limit yield, either due to deficiency or excess. Based on commercial yield and grower ratings the fields were divided into two groups: a) high yield fields rated as 'good' by the growers, and b) low yield fields rated as 'fair' or 'poor' by the growers. High yield was defined as greater than 800 cartons/acre for cauliflower, 900 cartons/acre for head lettuce and 1,000 cartons/acre for romaine. Low yield was defined as less than 700, 800 or 900 cartons per acre for cauliflower, head lettuce and romaine, respectively. Average yield for the high-yield fields was 940, 960 and 1230 cartons/acre for cauliflower, head lettuce, romaine, respectively; low-yield averages were 650, 590 and 590 cartons/acre, respectively. Fields of intermediate yield, and fields in which yield was affected by market conditions or other non-nutrient related factors were not used in the DRIS calculations.

For each crop at each growth stage the mean and variance for each possible ratio or product of each pair of nutrients (i.e. N/P, P/N, N*P) were calculated for both yield groups. For each nutrient pair the mean of the ratio or product that maximized the variance ratio between low- and high-yield groups was used in the DRIS calculations; the mean of the high-yield fields for that ratio or product became the DRIS 'norm' for that nutrient pair. A DRIS 'index' was calculated for each nutrient for each field and growth stage using the method of Walworth and Sumner (1987). In short, the relative abundance of each nutrient was evaluated by comparing all ratios or products containing that nutrient (i.e. N/P, N*K, Ca/N, etc.) with the DRIS norms. In the mathematical comparison an index value of zero indicated an optimum level, negative values a relative deficiency, and positive values a relative excess of that nutrient. DRIS indices were calculated for N, P, K, Ca, Mg, S, B, Zn, Mn, Fe, and Cu.

Each high-yield field was then evaluated for overall nutrient 'balance'; a field was considered balanced if all the individual nutrient indices were within 1.33 standard deviations (SD) of the mean for high-yield fields (Beaufils, 1973). Approximately 50% of high-yield fields had all nutrients in balance based on this criterion. Regression analysis was then performed on the data from these balanced, high-yield fields to determine the relationship between nutrient indices and leaf nutrient concentrations. From these regressions leaf nutrient sufficiency ranges were calculated, defined as the nutrient concentration corresponding to ± 1.33 SD around the zero value of each DRIS index. In theory, approximately 80% of high-yield fields would fall within these sufficiency ranges.

Data from the balanced, high-yield fields were used to generate sufficiency ranges for midrib NO_3-N, PO_4-P and K. From this subset of fields, sufficiency range for midrib concentrations was calculated by the method described for leaf total nutrient concentrations.

There are conflicting reports in the current literature about the effects of midrib sampling and handling practices on NO_3-N and PO_4-P concentrations; the uptake of these nutrient forms could be affected by short-term field environmental conditions, and the post-collection handling of midribs could influence the rate at which enzymatic activity in the plant assimilated these mineral nutrient forms into organic compounds. To determine the effect of weather conditions on midrib nutrient concentrations, daily reference evapotranspiration (ET_o) was obtained for the two days preceding the midseason sampling from the CIMIS weather station closest to each Salinas Valley lettuce field (head and romaine). There are no CIMIS weather stations currently operating in the Santa Maria area, so no ET_o estimates were available for fields in that region. To determine the effect of soil moisture and time of day of sample collection, one cauliflower, two romaine and three head lettuce fields were intensively sampled over an irrigation cycle. As soon as practical after an irrigation (day 2 in most cases) three replicate composite midrib samples were collected in the morning (before 11 AM), and again in the afternoon (after 1 PM). This AM/PM sampling was repeated at 2 day intervals twice more before the next irrigation.

To evaluate the effects of post-collection handling, a large sample of midribs were collected from two cauliflower, three head lettuce and two romaine. For each field this large sample was divided into 9 subsamples. Three replicate samples were immediately placed in a forced-air oven to dry. Three samples were placed in paper bags and held at room temperature for 24 hours before oven drying; the remaining 3 samples were refrigerated in plastic bags for 24 hours before oven drying.

To evaluate whether there are large differences among varieties in whole leaf nutrient concentrations, variety trials in two cauliflower and three lettuce fields were sampled at both the midseason and preharvest growth stages. There were four cauliflower varieties per field, and three lettuce varieties per field.

Results:

A. Field variablility

A wide range of soil physiochemical characteristics were encountered in the fields surveyed (Table 2). Soil texture varied from loamy sand to clay. The vast majority of fields had alkaline, low organic matter (< 2%) soil with high P and K fertility, conditions broadly representative of the coastal vegetable industry. High P availability stems from decades of heavy fertilization, which has raised P levels far above the native soil condition. More than 70% of fields sampled had bicarbonate extractable P > 50 PPM, the approximate level identified by recent FREP-sponsored research (Johnstone et al., 2005) as the agronomic threshold for lettuce response. DTPA extractable soil Zn, Mn, Fe and Cu were highly variable among fields. Compared with soil micronutrient levels reported for a wide range of California fields tested in the 1980s (Brown and deBoer, 1983) these coastal fields had, on average, higher extractable Zn and lower Fe, Mn, and Cu.

Variability in tissue analysis was equally broad; as an example, Table 3 lists the whole leaf and midrib nutrient concentration ranges for the midseason sampling. For many nutrients there was a three-fold difference or more between the maximum and minimum concentrations. Whole leaf macronutrient concentrations generally declined with each successive growth stage.

B. Whole leaf analysis

DRIS sufficiency ranges

Leaf nutrient concentrations of head and romaine lettuce were very similar (< 10% variation in mean values for all parameters measured at all growth stages; therefore, the data were combined in the DRIS calculations to develop a single set of nutrient sufficiency ranges for lettuce. Those macronutrient ranges are given in Table 4. For comparison, sufficiency ranges from several widely used references (Hochmuth et al., 1991; Jones et al., 1991; Ludwick, 2002) are listed as well.

The DRIS-derived sufficiency ranges were in general agreement with those given in the Western Fertilizer Handbook (Ludwick et al., 2002), a reference based in substantial part on earlier California research. The somewhat higher N ranges developed in this study were likely a function of widespread overfertilization, resulting in many fields having significantly higher leaf N concentration than would actually be required for optimum growth. The other references provide sufficiency ranges considerably different from the DRIS results, particularly with regard to leaf K, for which they list much higher values than typically seen in coastal fields.

DRIS cauliflower macronutrient leaf K sufficiency ranges were generally consistent with existing references, but were substantially higher than all references for N and P (Table 5). These higher N and P values undoubtedly reflected luxury consumption of those nutrients (plant uptake in excess of that required for maximum crop productivity), given the high soil P levels and the heavy N fertilization rates used in these fields. Given the limited number of balanced, high-yield cauliflower fields used to calculate these ranges, the DRIS N and P sufficiency ranges should be applied cautiously. Compared to lettuce, cauliflower had substantially higher leaf N and lower leaf K.

Lettuce and cauliflower had similar micronutrient sufficiency ranges (Tables 6 and 7). As expected, the exception was sulfur, which was 3-4 times higher in cauliflower. The DRIS ranges were close to existing reference values except for Ca, which we found to be in much lower concentration in lettuce and somewhat lower in cauliflower. The reason for this discrepancy is unclear; the majority of fields sampled in this study were alkaline, with Ca dominating the cation exchange, conditions that should maximize Ca uptake. It should be noted that leaf Ca concentration is related to leaf position. In this study the youngest wrapper leaf of lettuce and the leaf 3-4 nodes from the growing point in cauliflower were sampled; older leaves would have higher Ca concentration.

Of the micronutrients monitored, leaf molybdenum concentration had by far the lowest values, averaging 0.4 and 1.5 PPM at the midseason sampling for lettuce and cauliflower, respectively (Table 3). Given these very low concentrations relative to the analytical limit of detection (0.1 PPM), Mo was not included in the DRIS calculations; significant inaccuracy could be encountered in the calculation of ratios with other elements. For both crops the variability in leaf Mo among high-yield fields was such that a sufficiency range could not be calculated using the group mean and standard deviation. Alternatively, the relationship between leaf Mo and yield was evaluated using all fields (Fig. 1). Hochmuth et al. (1991) suggested that romaine leaf Mo > 0.1 PPM was adequate. In this study there was a weak trend toward lower lettuce yield at 0.2 PPM Mo than at higher concentrations, but that trend was not statistically significant; leaf concentrations of 0.3 PPM and higher were clearly not yield-limiting. Therefore, a leaf

Mo sufficiency level of 0.3 PPM appears justified for lettuce, with a deficiency level of < 0.2 PPM.

There was no apparent relationship between cauliflower leaf Mo and yield; in fact, high-yield fields had lower mean leaf Mo than low-yield fields. The much higher leaf Mo in cauliflower compared to lettuce (Table 3) suggested that cauliflower was better able to extract Mo from the soil, and therefore unlikely to encounter Mo deficiency in typical coastal fields.

Variety effects

The differences among varieties in leaf macronutrient concentration were minor; across fields and sampling stages, the standard deviation of variety concentrations averaged approximately 8% of the mean value for N, P and K. The practical impact of these data is that the DRIS sufficiency ranges should be representative across varieties.

Appropriate use of DRIS sufficiency ranges

To ensure that the DRIS-derived nutrient sufficiency ranges are appropriately used, several points need to be emphasized. If a field has tissue nutrient concentrations within these ranges, it is valid to assume that soil nutrient availability was sufficient for high-yield production. If a field has tissue nutrient concentrations above these ranges, it clearly suggests excessive nutrient availability; the farther above the sufficiency range, the more likely this excessive availability might be detrimental to crop productivity. However, tissue nutrient concentrations below the sufficiency ranges should not automatically be considered 'deficient', and limiting to plant growth. For some nutrients, luxury consumption may be common in coastal fields, whether as a result of naturally high soil levels (Fe, for example), or excessive fertilization (N or P, for example). For these nutrients the DRIS sufficiency ranges are substantially higher than reported in existing references. For these elements, low tissue concentrations should be considered deficient only it they fall substantially below the DRIS ranges.

Frequency of potential nutrient deficiency in commercial fields

To evaluate the extent to which yield-limiting nutrient deficiency may occur in coastal vegetable production, the percentage of low-yield fields falling below the DRIS sufficiency range was evaluated for each element. For the 25 low-yield lettuce fields the nutrient most frequently below the sufficiency range was Cu; > 40% of all low-yield fields fell below the Cu sufficiency range at both the midseason and preharvest growth stages. The significance of the low leaf Cu levels found in low-yield fields is unclear. The DRIS Cu sufficiency range closely matches those in current references, lending support for the validity of the range. The mean DTPA-extractable soil Cu level in these coastal soils was considerably lower than a set of nearly 200 California soils analyzed by Brown and deBoer (1983), suggesting that limited soil Cu availability is common in coastal vegetable soils. Unfortunately, the correlation of soil Cu to preharvest leaf Cu, although statistically significant ($r = 0.47$, $p < 0.01$), was not sufficiently robust to infer a distinct soil deficiency level (Fig. 2). Undesirably low leaf Cu appears most likely to occur in fields with DTPA-extractable soil Cu < 2 PPM.

For all other nutrients an approximately equal percentage of high- and low-yield fields fell below the sufficiency range, suggesting that yield-limiting deficiency of those nutrients is uncommon. (By the mathematical approach used in the DRIS calculations, for a given nutrient approximately 10% of high-yield fields would be expected to have leaf concentrations below the sufficiency range). Zn, historically the most commonly deficient micronutrient in much of California, fell below the DRIS leaf sufficiency range in only a couple of lettuce fields. The mean DTPA-extractable soil Zn in this study was 2.9 PPM, far higher than the 1.2 PPM average reported for 400 representative California soils analyzed in the 1980s (Brown and deBoer, 1983). Apparently, Zn fertilization in coastal fields since that time has remedied any historical Zn deficiency; none of the fields monitored had soil Zn < the 0.5 PPM agronomic threshold suggested by Brown and deBoer.

There were only 10 low-yield cauliflower fields, so caution must be used in inferring the frequency of nutrient deficiency in coastal fields. In 6 of these fields leaf Cu fell below the sufficiency range at the preharvest sampling. Leaf K was below the DRIS sufficiency range in 6 fields at the midseason sampling, and in 4 fields at the preharvest sampling. In all cases, fields with leaf K below the sufficiency range had soil exchangeable K < 150 PPM; there was no K fertilizer application in any of these fields.

Sodium and chloride toxicity

To evaluate the detrimental effects of Na and Cl on crop yield, the correlations of lettuce and cauliflower yield to leaf Na and Cl were determined for the preharvest sampling. For both crops there was a negative correlation between leaf Na and yield ($r = -0.28$ and -0.54 for lettuce and cauliflower, respectively, $p < 0.05$, Fig. 3). The slopes of the regressions were similar, indicating that the crops were about equally sensitive to high Na. Based on the linear regression equations, approximately 25 cartons/acre of potential yield was lost for each 0.1% increase in leaf Na. Lettuce yield was not significantly correlated with leaf Cl concentration, but cauliflower yield was ($r = -0.60$, $p < 01$, Fig. 4). Based on the linear regression equation, each 0.1% increase in leaf Cl reduced cauliflower yield by 17 cartons/acre.

C. Midrib analysis

DRIS sufficiency ranges

The California vegetable industry is unusual in its historical preference for using midrib analysis as the main diagnostic of plant nutrient status; whole leaf total nutrient analysis is more common in most other areas of the country. Of the tissue nutrient sufficiency references used, only the Western Fertilizer Handbook even lists midrib guidelines. The DRIS cauliflower midrib sufficiency ranges for all macronutrients, as well as the ranges for lettuce NO_3-N and K, were similar to those listed in the Western Fertilizer Handbook (Table 8). However, the DRIS lettuce midrib PO_4-P range was much lower than the existing standard, despite extremely high mean soil test P levels, and whole leaf P concentrations in line with previous references; approximately half of all high-yield fields had midrib PO_4-P concentrations below the 3,000 PPM sufficiency level given in the Western Fertilizer Handbook. Clearly, the DRIS sufficiency range is the more appropriate standard. There are no relevant standards against which to compare the DRIS ranges for the preharvest stage.

Variety effects on midrib nutrient concentration

The variability among varieties in midrib nutrient concentrations was similar to that in whole leaves. Across the variety trials sampled at the midseason and preharvest stages, the standard deviation of variety concentrations averaged approximately 8% of the mean value for NO_3-N, PO_4-P and K for lettuce, and 10% for cauliflower. We conclude that variety effects on midrib nutrient concentration are minor, and that the DRIS sufficiency ranges can be applied across varieties.

Effect of sampling and handling practices on midrib nutrient concentrations

Time of day of sample collection had no effect on midrib NO_3-N or PO_4-P concentration in either lettuce or cauliflower. Across the six fields sampled throughout an irrigation cycle, NO_3-N and PO_4-P concentrations in the AM samples averaged 12,000 and 2,250 PPM, respectively, compared to 11,990 and 2,260 PPM in PM samples. However, midrib NO_3-N was highly variable over relatively short time periods, changing as much as 30% within an irrigation cycle (Fig. 5). PO_4-P was somewhat less variable. One factor influencing this variability was the field environment. There was a significant negative correlation between the average daily ET_o in the two days preceding sample collection and lettuce midrib NO_3-N and PO_4-P ($r = -0.62$ and -0.40, respectively, $p < 0.05$, Fig. 6). Midrib concentrations declined with increasing ET_o (reflective of higher temperature and solar radiation), undoubtedly due to more rapid plant assimilation of these mineral N and P forms into organic compounds. This finding calls into question the value of midrib testing unless the nutrient concentrations are adjusted to reflect this weather-induced effect.

Post-collection handling of midrib samples had minimal impact. Holding samples for 24 hours either refrigerated or at room temperature before oven drying did not affect midrib NO_3-Nconcentration (Fig. 7); PO_4-P was similarly unaffected.

Relationship of midrib NO_3-N to soil NO_3-N

There was no correlation between midseason midrib NO_3-N and concurrently measured soil NO_3-N (Fig. 8). Even when corrected for the confounding effect of weather (as represented by ET_o), soil- and midrib NO_3-N concentrations were not significantly correlated. This lack of relationship between soil NO_3-N availability and midrib NO_3-N further undercuts the value of midrib testing as a fertilizer management tool.

D. Evaluation of grower fertilizer management practices

Several general conclusions regarding fertilizer management in coastal vegetable production can be drawn from this field survey. There was wide variation among fields in seasonal fertilizer application (Table 9). Where multiple fields were sampled on the same ranch it was common to find that a fertilization ‘recipe’ was followed, with no adjustments made for differences in soil characteristics or initial soil nutrient levels. As prior FREP-sponsored research has suggested, the higher end of N fertilization rates were clearly excessive; N fertilizer rate was unrelated to either lettuce yield or preharvest leaf N (Fig. 9).

A similar situation existed for P fertilizer management. A number of growers continued to apply P fertilizer in fields with soil test P far beyond the 50 PPM level identified by Johnstone et al. (2005) as the approximate agronomic response threshold for coastal lettuce (Fig. 10). That unnecessary P application had minimal effect on lettuce P concentration in fields with high soil test P level.

Conversely, some growers did not apply P fertilizer, even in fields with soil test P < 50 PPM. Using data only from lettuce fields not receiving P fertilization it was possible to correlate the preharvest leaf P with soil test level. Applying the resulting quadratic regression model ($r^2 = 0.29$, $p < 0.05$), the soil P level corresponding to the minimum DRIS leaf P sufficiency concentration (0.35%) was approximately 40 PPM bicarbonate-extractable P. To ensure adequate P nutrition it would appear that P fertilization is certainly appropriate in fields < 40 PPM soil test P; using the 50 PPM soil test threshold of Johnstone et al. would be a more conservative approach.

The ‘recipe’ approach to fertilization was also evident with K management, with a number of growers applying K irrespective of soil test K level (Fig. 11). Conversely, a number of fields with relatively low exchangeable soil K (< 150 PPM) did not receive K fertilization. Using data only from fields not receiving K fertilization, regression analysis of soil test K and preharvest leaf K was performed for both lettuce and cauliflower. From the quadratic regression equations ($r^2 = 0.45$ and 0.79 for lettuce and cauliflower, respectively, $p < 0.01$) an approximate agronomic threshold was calculated for soil K, defined as the soil K level corresponding to the lower limit of DRIS leaf K sufficiency. The soil K thresholds were approximately 100 PPM for lettuce and 140 PPM for cauliflower. K fertilization would certainly be recommended in fields below these thresholds; it may be prudent for growers to apply somewhat higher thresholds.

Literature cited:

Beaufils, E.R. 1973. Diagnosis and Recommendation Integrated System (DRIS). Soil Sci. Bull. 1, Univ. of Natal, South Africa.

Brown, A.L. and G.J. deBoer. 1983. Soil tests for zinc, iron, managenese and copper. In: H.M. Reisenauer (ed.). Soil and plant tissue testing in California. Univ. Calif. Bulletin 1879.

Hochmuth, G., D. Maynard, C. Vavrina and E. Hanlon. 1991. Plant tissue analysis and interpretation for vegetable crops in Florida. Univ. Florida Special Publication SS-VEC-42.

Johnstone, P.R., T.K. Hartz, M.D. Cahn and M.R. Johnstone. 2005. Lettuce response to phosphorus fertilization in high phosphorus soils. HortScience 40:1499-1503.

Jones, J.B., B. Wolf and H.A. Mills. 1991. Plant analysis handbook. Micro-Macro Publishing, Athens, GA, 213 pp.

Ludwick, A.E. (Ed.) 2002. Western fertilizer handbook, 9th Ed. Interstate Publishers, Inc., Danville, IL, 356 pp.

Walworth, J.L. and M.E. Sumner. 1987. The diagnosis and recommendation integrated system . Adv. Soil Sci. 6:149-188.

Table 1. Summary of soil and plant sampling and laboratory analysis.

Sample type	Growth stage	Analyses
soil	early	texture; pH; organic matter; Olsen P; NO_3-N; exchangeable K, Ca, Mg, Na; DTPA extractable Zn, Mn, Fe, Cu; saturated paste B
	midseason	NO_3-N
	preharvest	NO_3-N
whole plants (early stage) or whole leaf	all	total N, P, K, Ca, Mg, S, Zn, Mn, Mo, Cu, Fe, B, Na, Cl
midribs	midseason and preharvest	NO_3-N, PO_4-P, K

Table 2. Range of soil physiochemical characteristics in sampled fields.

	pH	Organic matter (%)	Olsen P (PPM)	Exchangeable K (PPM)	Exchangeable cations (meq/100 g)			DTPA extractable micronutrients (PPM)			
					Ca	Mg	Na	Zn	Mn	Fe	Cu
Mean	7.4	1.60	68	290	15.4	4.5	0.7	2.9	16.2	18.5	2.6
Maximum	8.0	4.50	156	1177	38.8	15.9	4.6	10.6	53.8	51.3	11.6
Minimum	6.6	0.60	16	87	5.6	1.5	0.2	0.5	3.5	3.7	0.3

Table 3. Range of tissue nutrient concentrations encountered in sampled fields at the midseason sampling.

	Unit	Lettuce			Cauliflower		
		mean	max	min	mean	max	min
				whole leaf			
N	%	4.7	6.0	3.1	5.5	7.9	2.9
P	%	0.58	0.85	0.37	0.67	0.97	0.38
K	%	4.8	7.7	2.5	2.9	4.8	1.5
Ca	%	0.6	1.1	0.4	1.9	3.8	0.5
Mg	%	0.3	0.5	0.2	0.4	0.9	0.3
S	%	0.3	0.4	0.2	1.0	1.4	0.5
Zn	PPM	50	108	13	46	84	17
Mn	PPM	54	116	21	43	84	19
Fe	PPM	151	504	72	128	228	70
Cu	PPM	6.8	13.4	2.9	5.2	9.6	2.7
B	PPM	25	45	14	26	34	19
Mo	PPM	0.4	1.1	0.2	1.5	7.0	0.3
				midrib			
NO_3-N	PPM	7,410	15,110	410	9,850	20,100	1,820
PO_4-P	PPM	2,600	4,180	1,190	3,910	6,010	2,520
K	%	6.5	9.5	2.8	4.2	6.8	2.7

Table 4. DRIS-derived whole leaf macronutrient sufficiency ranges for lettuce, with comparative ranges from current reference sources.

Source	Stage	N	P	K
DRIS	early	4.7 - 5.6	0.45 - 0.70	3.7 - 7.3
	midseason	4.3 - 5.1	0.45 - 0.75	3.3 - 6.4
	preharvest	3.3 - 4.8	0.35 - 0.75	2.9 - 7.8
Sufficiency reference:				
#1 Head	midseason	3.0 - 4.0	0.40 - 0.85	3.0 - 4.0
#2 Head	midseason	2.5 - 4.0	0.40 - 0.60	4.5 - 8.0
#3 Head	preharvest	3.8 - 5.0	0.45 - 0.60	6.6 - 9.0
#2 romaine	preharvest	3.5 - 4.5	0.35 - 0.60	5.0 - 6.0
#3 romaine	preharvest	3.5 - 4.5	0.45 - 0.80	5.5 - 6.2

DRIS sufficiency ranges derived from combined analysis of head and romaine fields, and are applicable to both types

Sufficiency references: 1) Western Fertilizer Handbook (Ludwick, 2002); 2) University of Florida Publication SS-VEC-42 (Hochmuth et al., 1991); 3) Plant Analysis Handbook (Jones et al., 1991)

Table 5. DRIS-derived whole leaf macronutrient sufficiency ranges for cauliflower, with comparative ranges from current reference sources.

Source	Stage	N	P	K
DRIS	early	5.5 - 6.7	0.50 - 0.70	2.6 - 3.7
	midseason	5.4 - 7.9	0.65 - 1.05	2.7 - 4.6
	preharvest	4.3 - 5.9	0.55 - 1.00	2.0 - 4.7
Sufficiency reference:				
#1	midseason	3.0 - 5.0	0.50 - 0.70	2.6 - 4.1
#2	midseason	3.0 - 5.0	0.40 - 0.70	2.0 - 4.0
#3	midseason	3.3 - 4.5	0.33 - 0.80	2.6 - 4.2

Sufficiency references: 1) Western Fertilizer Handbook (Ludwick, 2002); 2) University of Florida Publication SS-VEC-42 (Hochmuth et al., 1991); 3) Plant Analysis Handbook (Jones et al., 1991)

Table 6. DRIS-derived micronutrient sufficiency ranges for lettuce, with comparative ranges from current reference sources.

Source	Stage	% Ca	% Mg	% S	PPM Zn	PPM Mn	PPM Fe	PPM Cu	PPM B
DRIS	early	1.0 - 1.3	0.40 - 0.60	0.30 - 0.40	35 - 55	40 - 95	300 - 800	5.6 - 9.6	15 - 30
	midseason	0.45 - 0.75	0.25 - 0.40	0.25 - 0.35	20 - 75	35 - 75	85 - 230	5.6 - 8.2	20 - 30
	preharvest	0.6 - 1.1	0.25 - 0.45	0.20 - 0.35	25 - 75	45 - 75	115 - 255	5.0 - 8.6	25 - 35
Sufficiency reference:									
#2 Head	midseason	1.4 - 2.0	0.30 - 0.70	> 0.30	25 - 50	20 - 40	50 - 150	5 - 10	15 - 30
#3 Head	preharvest	1.5 - 2.3	0.36 - 0.50		25 - 250	25 - 250	50 - 100	7 - 25	23 - 50
#2 Romaine	preharvest	2.0 - 3.0	0.25 - 0.35		20 - 50	15 - 25		5 - 10	30 - 45
#3 Romaine	preharvest	2.0 - 2.8	0.60 - 0.80		20 - 250	11 - 250	40 - 100	5 - 20	25 - 60

DRIS sufficiency ranges derived from combined analysis of head and romaine fields, and are applicable to both types
Sufficiency references: 2) University of Florida Publication SS-VEC-42 (Hochmuth et al., 1991); 3) Plant Analysis Handbook (Jones et al., 1991)

Table 7. DRIS-derived micronutrient sufficiency ranges for cauliflower, with comparative ranges from current reference sources.

Source	Stage	% Ca	% Mg	% S	PPM Zn	PPM Mn	PPM Fe	PPM Cu	PPM B
DRIS	early	1.4 - 3.3	0.30 - 0.80	0.6 - 1.7	25 - 70	30 - 70	110 - 200	4.0 - 7.0	15 - 35
	midseason	0.6 - 2.2	0.25 - 0.45	1.0 - 1.4	35 - 70	30 - 50	120 - 160	5.4 - 8.4	25 - 35
	preharvest	0.5 - 2.5	0.20 - 0.60	0.8 - 1.2	30 - 75	20 - 75	70 - 195	3.6 - 6.9	20 - 35
Sufficiency reference:									
#2	midseason	0.8 - 2.0	0.25 - 0.60	0.6 - 1.0	30 - 50	30 - 80	30 - 60	5 - 10	30 - 50
#3	midseason	2.0 - 3.5	0.27 - 0.50		20 - 250	25 - 250	30 - 200	4 - 15	30 - 100

Sufficiency references: 2) University of Florida Publication SS-VEC-42 (Hochmuth et al., 1991); 3) Plant Analysis Handbook (Jones et al., 1991)

Table 8. DRIS-derived midrib sufficiency ranges for lettuce and cauliflower, with comparative ranges from the Western Fertilizer Handbook.

Crop	Source	Stage	NO_3-N	PO_4-P	K
Lettuce	DRIS	midseason	5,000 - 11,500	1,800 - 3,600	5.1 - 8.2
		preharvest	3,600 - 14,900	1,700 - 5,000	4.8 - 10.3
	Western Fertilizer Handbook	midseason	6,000 - 10,000	3,000 - 4,000	4.5 - 7.5
Cauliflower	DRIS	midseason	5,700 - 13,800	3,800 - 5,500	4.2 - 6.5
		preharvest	2,100 - 10,900	2,900 - 6,400	2.8 - 4.7
	Western Fertilizer Handbook	midseason	6,000 - 12,000	3,500 - 5,000	4.0 - 6.0

Table 9. Macronutrient fertilizer application in survey fields.

		Seasonal fertilizer application (lb / acre)		
Crop	Nutrient	mean	max	min
Head lettuce	N	173	392	47
	P_2O_5	34	94	0
	K_2O	26	78	0
Romaine lettuce	N	155	267	27
	P_2O_5	41	111	0
	K_2O	36	84	0
Cauliflower	N	264	459	116
	P_2O_5	19	120	0
	K_2O	19	100	0

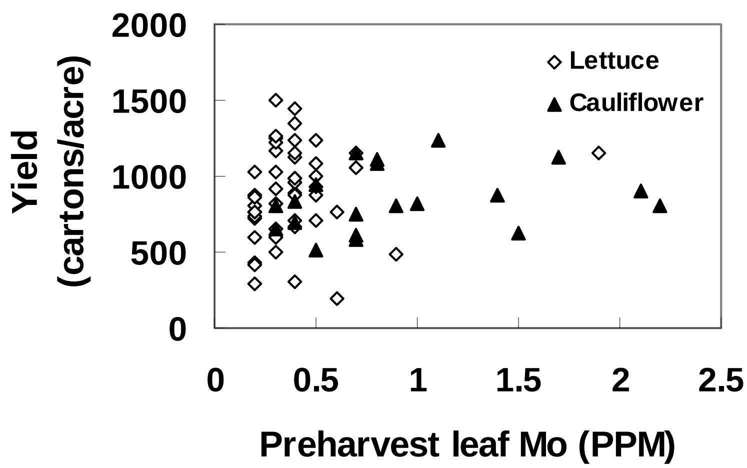

Fig. 1. Relationship between yield and leaf Mo concentration at the preharvest sampling.

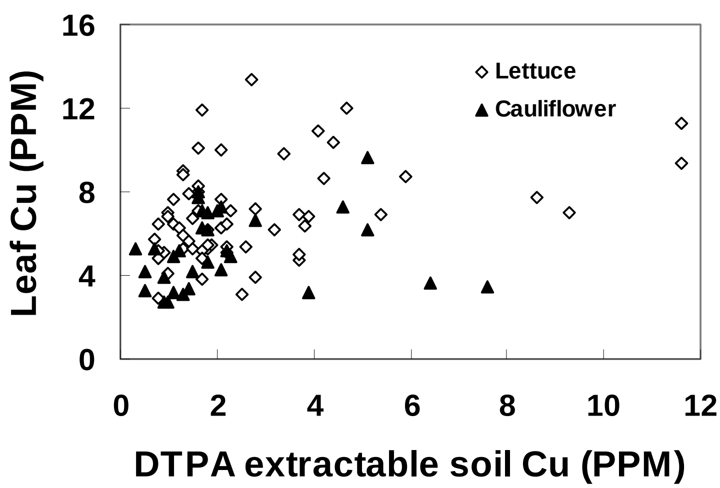

Fig. 2. Relationship between DTPA-extractable soil Cu and leaf Cu concentration at the preharvest sampling.

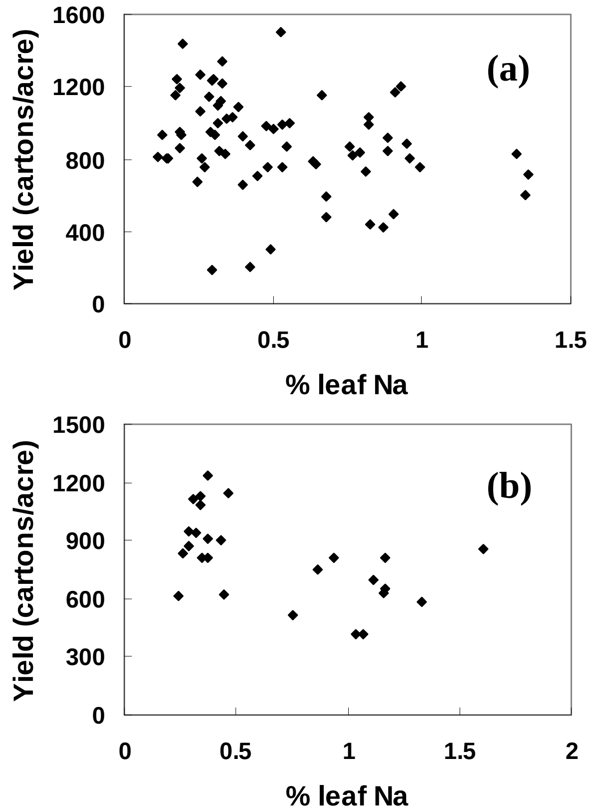

Fig. 3. Relationship between preharvest leaf Na concentration and lettuce yield (a, r = -0.28) or cauliflower (b, r = -0.54).

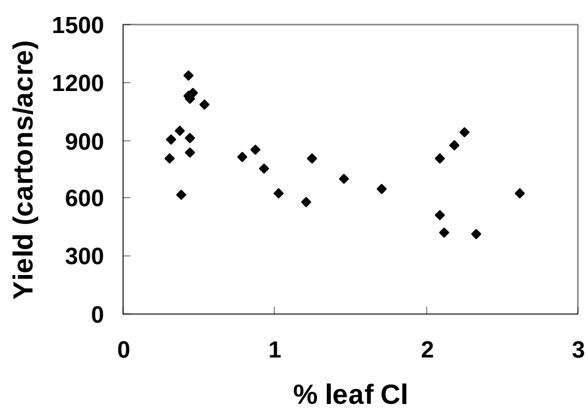

Fig. 4. Relationship between preharvest leaf Cl and cauliflower yield (r = -0.60).

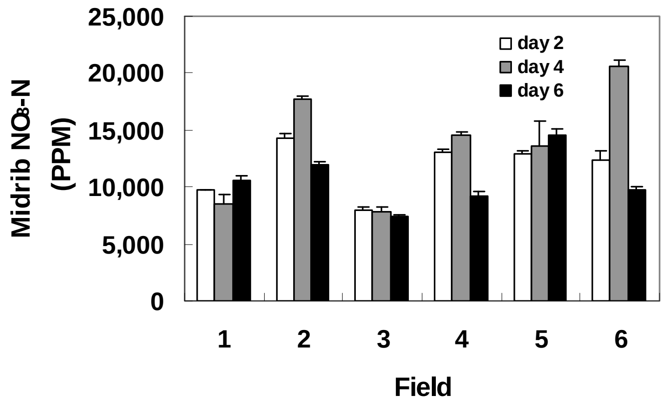

Fig. 5. Variability in midrib NO_3-N concentration over an irrigation cycle; fields sampled every 2 days after an irrigation. Bars indicate standard error of measurement.

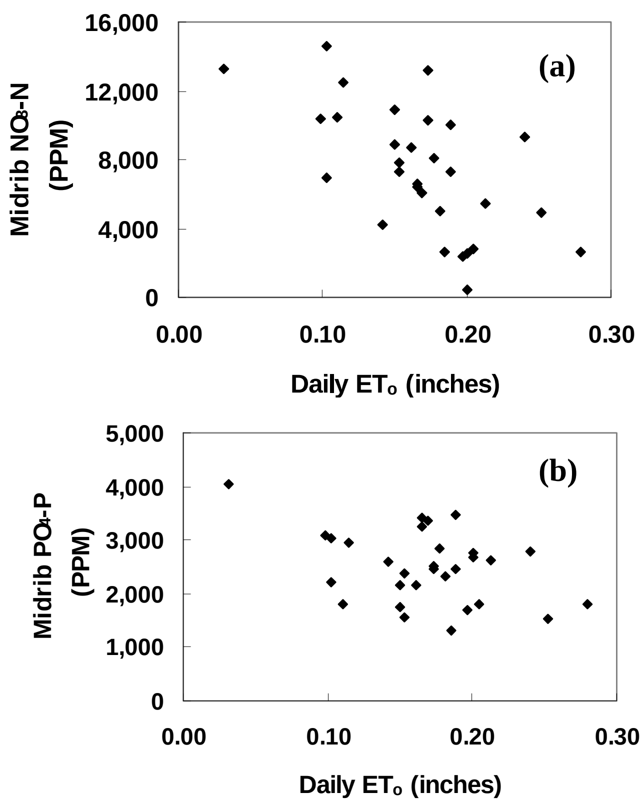

Fig. 6. Effect of average daily reference evapotranspiration (ET_o) in the two days prior to sample collection on midseason midrib NO_3-N (a, r = -0.62) and PO_4-P (b, r = -0.40).

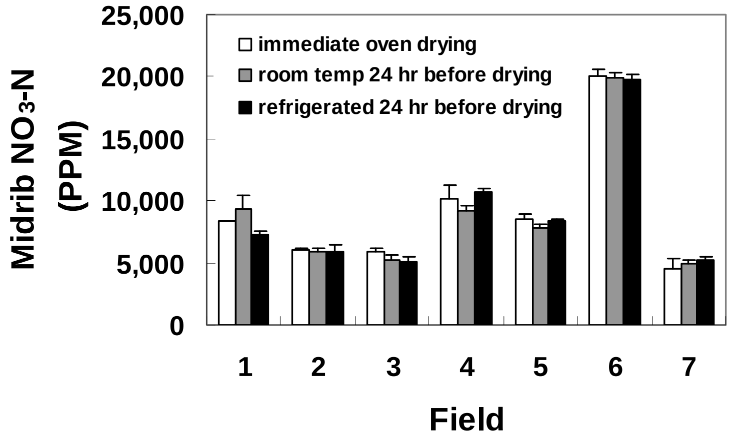

Fig. 7. Effect of post-collection handling practice on midrib NO_3-N concentration. Bars indicate standard error of measurement.

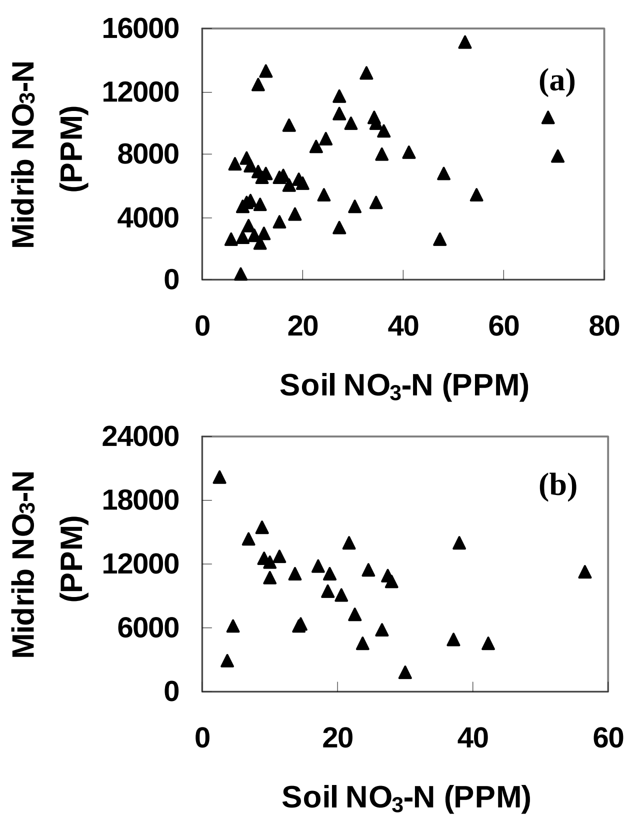

Fig. 8. Relationship between midseason midrib NO_3-N in lettuce (a) or cauliflower (b) and concurrently measured soil NO_3-N.

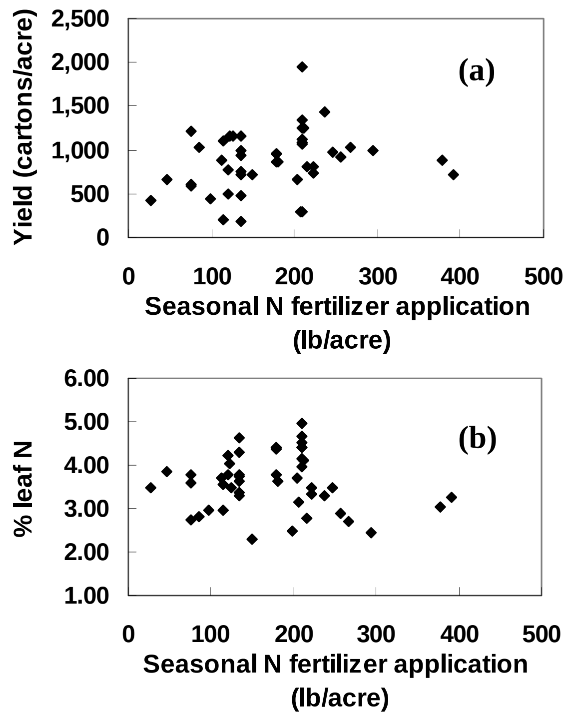

Fig. 9. Relationship between seasonal N application rate and lettuce yield (a) or preharvest leaf N (b).

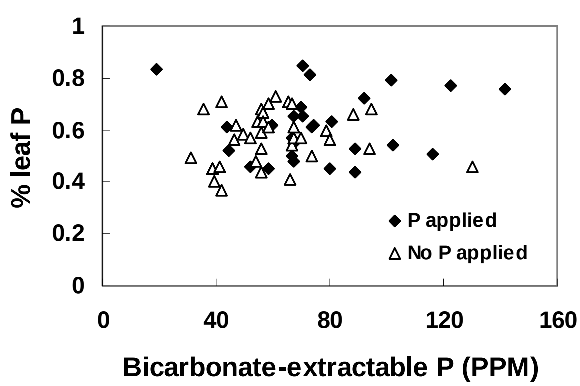

Fig. 10. Influence of soil test P and P fertilization on midseason leaf P.

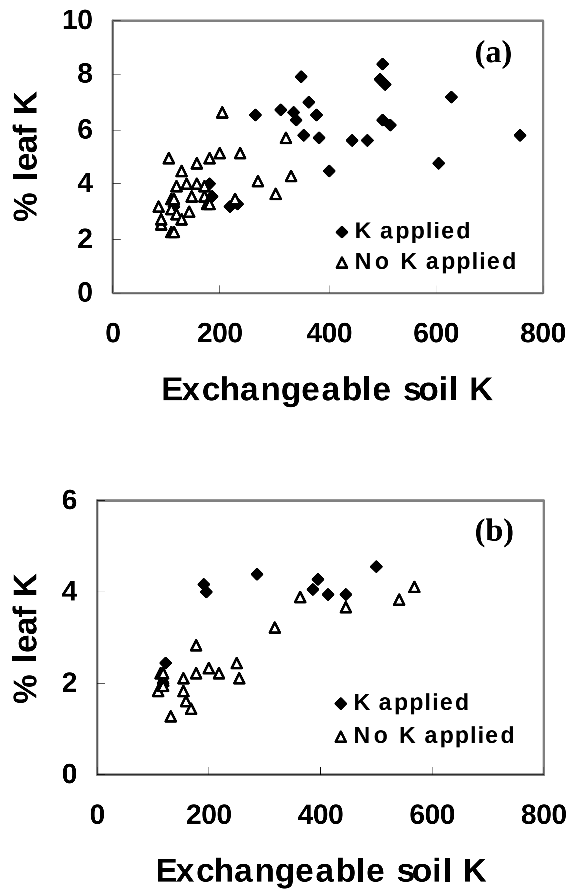

Fig. 11. Effect of exchangeable soil K and K fertilizer application on preharvest leaf K concentration in lettuce (a) and cauliflower (b).